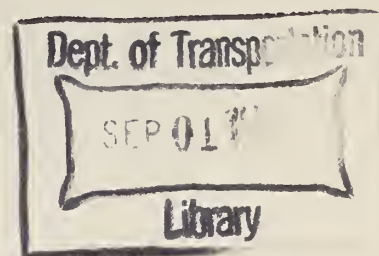


TL
242
.H36
v.1

DOT HS-802 410

ON-BOARD VEHICLE SENSOR TECHNOLOGY

Volume I-Summary Report



Contract No. DOT-HS-5-01178

June 1977

Final Report

PREPARED FOR:

**U.S. DEPARTMENT OF TRANSPORTATION
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION
WASHINGTON, D.C. 20590**

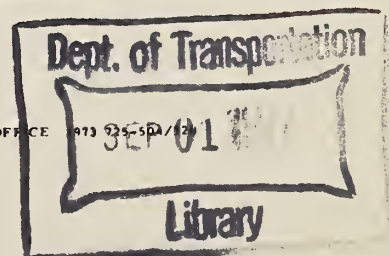
Document is available to the public through
the National Technical Information Service,
Springfield, Virginia 22161

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

1. Report No. DOT HS 802 410	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle On-Board Vehicle Sensor Technology Volume I, - Summary Report		5. Report Date June 1977	6. Performing Organization Code
		8. Performing Organization Report No. AVSD-0353-76-RR	
7. Author(s) R. Heldt, H. Burke		10. Work Unit No. (TRAIS)	11. Contract or Grant No. DOT-HS-5-01178
9. Performing Organization Name and Address Avco Systems Division 201 Lowell Street Wilmington, Massachusetts 01887		13. Type of Report and Period Covered Final June 1975-December 1976	
		14. Sponsoring Agency Code	
12. Sponsoring Agency Name and Address Department of Transportation National Highway Traffic Safety Administration NASSIF Bldg., 400 7th St., S.W. Washington, D.C. 20690		15. Supplementary Notes	
16. Abstract Forty three areas were identified in the brake, steering, suspension, tire, lighting and signalling systems where safety or inspection benefits might be obtained through the application of on-board vehicle sensors utilizing either on-board or off-board readout. These areas were screened against a variety of criteria, the most important being their potential for accident reduction as determined in the Indiana Tri-Level Studies in Accident Causation. Eleven areas were judged to warrant detailed evaluation of implementation considerations. These eleven candidate areas were then subjected to further analysis including identification of: currently available hardware, existing techniques for sensor application, conceptual devices where hardware does not now exist, and improvements possible in existing devices. In addition, a cost benefit analysis was performed for each candidate area, utilizing estimates of sensor life-cycle cost and benefit, including both safety and other impacts. These results are preliminary in nature, due to the weakness of the data bases in all important areas. Limited consideration was also given to alternative countermeasures in each area. Four candidate areas are judged to offer the potential of a favorable benefit/cost ratio. These are brake performance, tire tread depth, brake lights and brake friction material.			
17. Key Words Sensor, Safety Criticality, Cost Benefit Analysis, Vehicles-In-Use, Periodic Motor Vehicle Inspection		18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 28	22. Price

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized



METRIC CONVERSION FACTORS

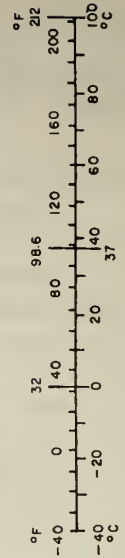
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in = 2.54 exact; 1 ft = other exact conversions, and more data, in tables, see ABS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25, SO Catalog No. C1211C286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	
MASS (weight)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

1.0	INTRODUCTION	1
2.0	CANDIDATE AREAS	2
3.0	EVALUATION OF SENSOR TECHNIQUES	7
3.1	Overview of Methodology and Results	7
3.2	Evaluation of Potentially Cost Beneficial Sensors	13
3.2.1	Brake Performance	13
3.2.2	Tire Tread Wear	15
3.2.3	Brake Light	16
3.2.4	Brake Wear	16
4.0	CONCLUSIONS	18
4.1	Technical Conclusions	18
4.2	Critical Conclusions	19
5.0	RECOMMENDATIONS	22
5.1	Recommendations for Advancement of Sensor Technology ..	22
5.2	Recommendations for Data Base Improvement	23

ILLUSTRATIONS

Figure 2-1	Algorithm of Test Criteria for Establishing Sensor Candidacy	3
3-1	Brake Performance Sensor (Five Transducer Version)	14

TABLES

Table 2-1	Identification of Candidate Sensor Areas	5
2-2	Sensor Areas Evaluated in Task 3	6
3-1	Safety Criticality of Components Monitored by Candidate Sensors	8
3-2	Revised Accident Benefit of Sensors	10
3-3	Potential Economic Impacts of On-Board Sensors	10
3-4	Results of Evaluation - Candidates for On-Board Readout	11
3-5	Results of Evaluation - Candidates for Off-Board Readout	12

1.0 INTRODUCTION

The Onboard Vehicle Sensor Technology Program has been a research effort, assessing the state-of-the-art and potential areas of future development of on-board vehicle sensors and deriving their applicability to passenger car brake, steering, suspension, tire, lighting and signaling systems.

In its introduction to the statement of work, NHTSA states:

"The National Highway Traffic Safety Administration (NHTSA) believes that automobiles equipped with on-board vehicle sensors for the continuous and/or periodic monitoring of safety critical systems, subsystems, and components could have a substantial impact on highway safety."

The specific objectives called out in the original statement of work are:

1. Identify candidate subsystems and components in the brake, tire, steering, suspension, lighting, and signaling systems from which inspection and safety benefits may be obtained by means of on and off-board sensor techniques.
2. Determine specifically those candidate subsystems and components which require monitoring using on-board vehicle sensors and those requiring only periodic surveillance using off-vehicle equipment in conjunction with an interface device.
3. Develop, validate and recommend optimum on-board sensor systems for both continuous and/or periodic monitoring of safety critical subsystems, and components.

In addition, because on-board vehicle sensors are one possible counter-measure aimed at the more general problem of vehicles-in-use (VIU) degradation, work performed under this program has illuminated several important issues common to the analysis of all VIU countermeasures.

Three individual tasks* have been carried out to fulfill the specific objectives listed above. Task 2 involved determination of where to apply sensors, based on accident data and other sources. It also involved resolution of whether the read-out should be on-board or off-board. Task 3 involved determination of how to provide sensing in the selected areas. Finally, (Task 4) selected sensors from Task 3 were tested and display models were constructed and delivered to NHTSA.

*Tasks 2 through 4. Task 1 was the preparation of a plan-of-work and methodology, and is not specifically described in this report.

2.0 CANDIDATE AREAS

The determination of candidate areas for sensor application (and whether to provide on-board readout) was (by SOW requirement) based on the following criteria:

- Historical vehicle accident data.
- Performance degradation data.
- Failure data.
- Subsystem/component fault frequencies.
- Motor vehicle inspection problems.
- Inspection data.
- Inspection technology.

These criteria were restructured into a ten-step evaluation algorithm whose application has involved answering the following questions:

1. Can the safety benefit be documented in accident records?
2. Does component degradation significantly affect limit performance?
3. Does component failure create an immediate safety hazard?
4. Does the component fail frequently?
5. Does sensing of the component offer a consumer benefit?
6. Is it practical to provide real time readout to the driver?
7. Will the safety benefit of sensing be significant relative to PMVI?
8. Is off-board readout possible?
9. Would the on-board sensor provide superior inspection?
10. Would the on-board sensor and associated readout devices cost significantly more than present inspection technique?

These questions have been structured as shown in Figure 2-1 so that candidate areas could be identified with a minimum of redundant research

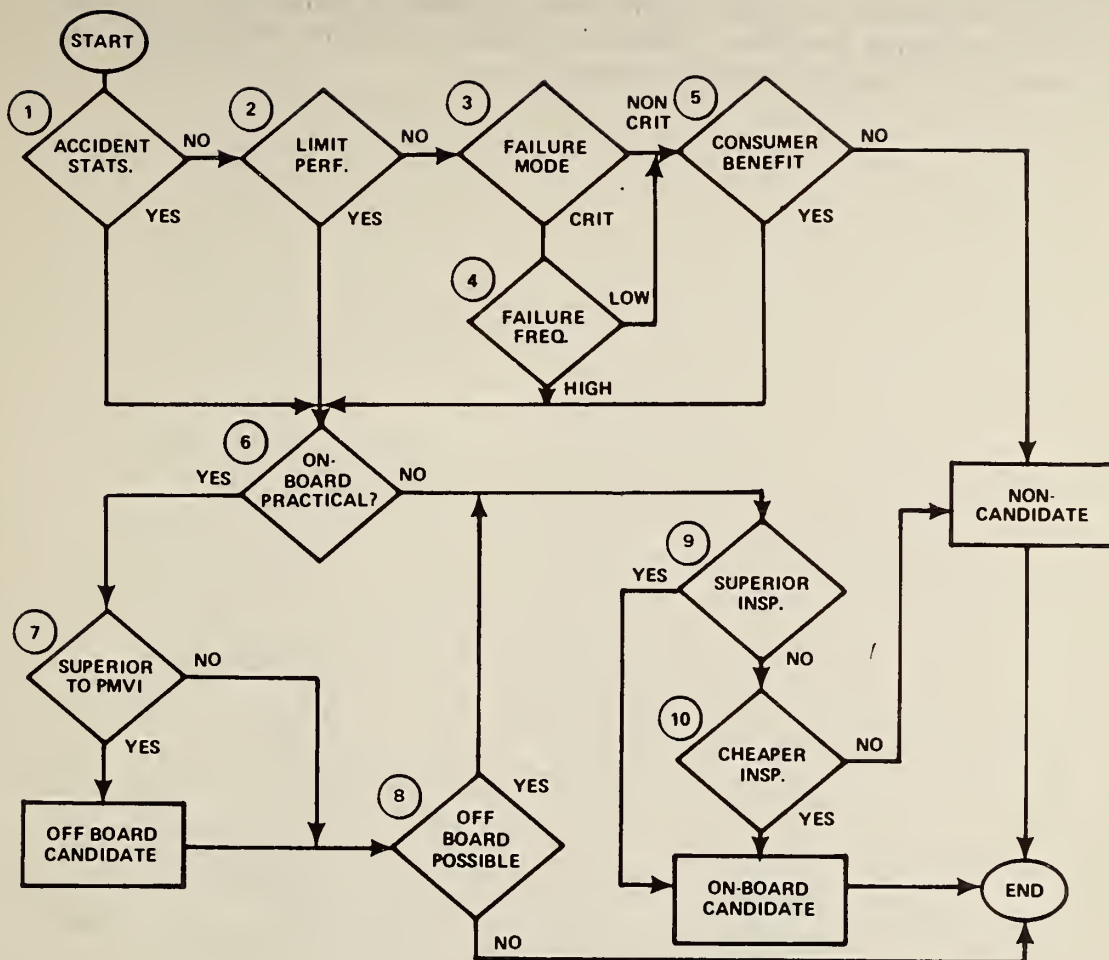


Figure 2-1 ALGORITHM OF TEST CRITERIA FOR ESTABLISHING SENSOR CANDIDACY

activity. For example, if a sensor area could be justified on the basis of accident data, detailed consideration was not given to laboratory performance studies involving the same defect.

The list of sensor areas considered, and the outcome of its evaluation against the ten criteria is depicted in Table 2-1. The eleven sensor areas considered as candidates for consideration in Task 3 are identified by the symbol c in the right-hand column of this table. These candidate sensors are also listed in Table 2-2, with identification of the read-out modes deemed most appropriate.

TABLE 2-1. IDENTIFICATION OF CANDIDATE SENSOR AREAS

RESULTS OF SCREENING PROCESS		ACCIDENT STATUS	LIMIT PERF.	FAILURE MODE	FAILURE FREQ.	CONSUMER BENEFIT	ON-BOARD READOUT FEAS.	SUPERIOR TO FMT	OFF-BOARD POSSIBLE	SUPERIOR INSP.	CHEAPER INSP.	CANDIDATE
<u>SUSPENSION</u>												
1	WHEEL BEARING'S CONDITION	N	N	N	-	N	-	-	-	-	-	
2	WHEEL (SPINDLE, STEERING KNUCKLE) INTEGRITY (FRONT ONLY)	N	N	Y	N	N	-	-	-	-	-	
3	BALL JOINT OR KING PIN CONDITION (FRONT ONLY)	N	N	Y	N	N	-	-	-	-	-	
4	SHOCK ABSORBER CONDITION	N	Y	-	-	-	Y	N	Y	Y	-	C
5	SPRING CONDITION	N	N	Y	N	N	-	-	-	-	-	
6	CONTROL ARMS AND STABILIZER BUSHINGS CONDITION	N	N	N	-	N	-	-	-	-	-	
7	FASTENER AND BRACKET INTEGRITY OR CONDITION	N	N	Y	N	N	-	-	-	-	-	
8	WHEEL FASTENER CONDITION	N	N	Y	N	N	-	-	-	-	-	
9	LUBRICATION STATUS	N	N	N	-	N	-	-	-	-	-	
<u>STEERING</u>												
10	STEERING WHEEL PLAY	Y	-	-	-	-	Y	N	Y	Y	-	C
11	LINKAGE INTEGRITY/CONDITION	N	N	N	-	N	-	-	-	-	-	
12	WHEEL ALIGNMENT (CASTER, CAMBER, TOE)	N	N	N	-	Y	Y	N	Y	Y	-	C
13	FASTENER AND BRACKET INTEGRITY OR CONDITION	N	N	Y	N	N	-	-	-	-	-	
14	LUBRICATION STATUS	N	N	N	-	N	N	-	Y	Y	-	
15	POWER STEERING FLUID LEVEL/FLUID FLOW	N	N	Y	N	N	-	-	-	-	-	
16	POWER STEERING BELT STATUS	N	N	Y	N	N	-	-	-	-	-	
16A	EXCESS TORQUE	N	N	Y	N	N	-	-	-	-	-	
<u>LIGHTING</u>												
17	HEADLIGHT AIM	N	N	N	-	N	-	-	-	-	-	
18	HEADLIGHT AND RUNNING LIGHT STATUS (INTENSITY)	N	N	N	-	N	-	-	-	-	-	
19	LENS INTEGRITY	N	N	N	-	N	-	-	-	-	-	
20	CIRCUIT ELEMENT (RELAYS, SWITCHES, FUSE CIRCUIT BREAKER, WIRE, CONNECTORS) STATUS	N	N	N	-	N	-	-	-	-	-	
21	PAD AND LINING WEAR	Y	-	-	-	-	Y	Y	Y	Y	Y	C
22	RESERVOIR LEVEL	N	N	Y	N	N	-	-	-	-	-	
23	FLUID LEAK TO BRAKES	Y	-	-	-	-	Y	Y	Y	Y	Y	C
23A	GREASE LEAK	N	N	Y	N	N	-	-	-	-	-	
24	DRUM/ROTOR INTEGRITY/STRENGTH	N	N	Y	N	N	-	-	-	-	-	
25	FLEX-LINE/RIGID LINE INTEGRITY	N	N	Y	N	N	-	-	-	-	-	
26	BRAKE FLUID CONTAMINATION (WATER)	N	N	N	-	N	-	-	-	-	-	
27	DRUM BRAKE ADJUSTMENT STATUS	N	N	N	-	N	-	-	-	-	-	
28	SYSTEM IMBALANCE	Y	Y	-	-	-	Y	Y	Y	Y	Y	C
29	ROTOR/DRUM TEMPERATURE	N	N	Y	N	N	-	-	-	-	-	
29A	TRAIL OVERTRAVEL	N	N	Y	N	N	-	-	-	-	-	
29B	LINKAGE OPERATION	N	N	N	-	N	-	-	-	-	-	
<u>SIGNALING SYSTEMS</u>												
TURN INDICATORS AND 4-WAY FLASHER												
30	LIGHT STATUS (INTENSITY)	N	N	N	-	N	-	-	-	-	-	
31	FLASH RATE	N	N	N	-	N	-	-	-	-	-	
32	CANCELLATION STATUS	N	N	N	-	N	-	-	-	-	-	
33	CIRCUIT ELEMENT STATUS	N	N	N	-	N	-	-	-	-	-	
34	LENS INTEGRITY	N	N	N	-	N	-	-	-	-	-	
<u>HORN</u>												
35	ONE HORN FAILURE IN DUAL HORN SYSTEM	N	N	N	-	N	-	-	-	-	-	
36	CIRCUIT ELEMENT STATUS	N	N	N	-	N	-	-	-	-	-	
<u>BRAKE LIGHTS</u>												
37	LIGHT STATUS (INTENSITY)	Y	-	-	-	-	Y	Y	Y	N	N	C
38	LENS INTEGRITY	N	N	N	-	N	-	-	-	-	-	
39	CIRCUIT ELEMENT STATUS (ELECTRICAL)	Y	-	-	-	-	Y	Y	Y	N	N	C
<u>TIRES</u>												
40	TIRE PRESSURE (UNDER INFLATED)	Y	-	-	-	-	Y	Y	Y	N	N	C
40A	TIRE PRESSURE (OVER INFLATED)	N	N	N	-	N	-	-	-	-	-	
41	TIRE INTEGRITY	N	-	Y	Y	-	N	-	Y	Y	-	C
42	TREAD DEPTH	Y	-	-	-	-	N	-	Y	Y	-	C
43	WEAR PATTERN	N	N	N	-	N	-	-	-	-	-	

N = NO
Y = YES
C = CANDIDATE

TABLE 2-2. SENSOR AREAS EVALUATED IN TASK 3

Candidate Area	Method of Readout	
	On-board	Off-board
Brake performance	X	X
Tire pressure	X	
Tire tread depth		X
Brake light intensity	X	
Brake light function	X	
Steering wheel play		X
Brake pad and lining wear	X	X
Brake friction material contam by fluid	X	X
Tire integrity		X
Shock absorbers		X
Front end alignment		X

/

3.0 EVALUATION OF SENSOR TECHNIQUES

In this task, the eleven candidate areas identified in Table 2-2 have been researched to

- determine what sensors are presently on the market, their capabilities, shortcomings and cost.
- define concepts for sensor applications not currently available and estimate their performance and cost.

The information developed on sensor performance and cost has been included in a cost-benefit analysis for each of the sensor areas. This analysis has included consideration of the following factors, measured over a 12 year vehicle lifetime:

- Accident cost.
- Cost of sensor, including maintenance.
- Economic impacts (vehicle tire wear, fuel consumption, maintenance).
- Cost of periodic inspection.

3.1 OVERVIEW OF METHODOLOGY AND RESULTS

The societal economic cost of motor vehicle accidents has been estimated (using NHTSA data) at \$40 billion for the year 1974. This maps into a cost (in 1975 dollars) of about \$336 per vehicle per year.

Detailed examination of the best available references on vehicle factors in accident causation indicates that perhaps 7.5% of all accidents would be caused by vehicle factors, assuming current vehicle design and no periodic inspection, nationwide. In most of these cases, an on-board vehicle sensor capable of detecting the defective condition can be envisaged. The impact of on-board sensors, therefore, is bounded by 7.5% of the national accident total.

This implies a maximum national economic benefit of \$3.0 billion (1974 dollars) annually, or about \$302 per vehicle lifetime for all sensors.

Obviously, it is not possible to provide sensors for every component of the vehicle, yet remain within the (implied) cost constraint. The total contribution for in-use defects (7.5% of all accidents) has therefore been subdivided among the systems of the vehicle, thereby establishing the areas with the greatest benefit. The results of this subdivision are indicated in Table 3-1.

TABLE 3-1. SAFETY CRITICALITY OF COMPONENTS MONITORED
BY CANDIDATE SENSORS

Area	Safety criticality (% of all accidents)	Lifetime cost of accidents (\$)
Brake performance	3.19	128.62
Tire pressure	0.97	39.11
Tire tread	1.13	45.56
Brake light intensity	0.12	4.84
Brake light electrical	0.12	4.84
Brake pad and lining wear	1.14	45.96
Steering wheel play	0.26	10.48
Brake fluid leaks	1.01	40.72
Shock absorber	0.23	9.27
Front end alignment	0.05	2.02
Tire integrity	0.10	4.03
Total*	6.05	243.94

*This is not the algebraic sum of the entries since some areas are overlapping.

These figures represent an upper bound for the safety benefit derived from sensor application. Four additional steps must occur before a safety benefit is realized.

1. The sensor must detect the condition.
2. The alarm must be perceived by the driver; i.e., it must gain his attention.
3. The indication must be comprehended; the driver must know what the display means.
4. The driver must take (immediate) corrective action.

In general, none of these processes is 100% reliable. With off-board readout, for example, the sensor may not be interrogated sufficiently often to achieve maximum benefit. Moreover, the accident investigation literature contains numerous examples of persons who were aware of defects in their vehicle, yet chose to ignore them.

Some of these real world effects have been considered in the formulation of Table 3-2 which provides a more conservative estimate of the lifetime safety benefit of sensors in the 11 candidate areas. Although it is possible that sensors will stimulate corrective action from persons who would otherwise ignore a defect, this effect is countered by the assumption of 100% sensor/display reliability.

Table 3-3 summarizes the economic impacts potentially obtainable through on-board sensor application. For certain sensors, these estimates have been scaled down to reflect practical considerations. For example, a brake performance sensor has been evaluated on the basis of no savings in disc/drum refinishing, and a savings of 35% (\$11) in disc/drum replacement.

Tables 3-4 and 3-5 summarize the overall process of sensor evaluation. These tables are organized according to the two modes of readout evaluated.

Considering the limitations of the data bases which have supported this analysis, any determination that certain on-board vehicle sensors are (or are not) cost beneficial is necessarily tentative. However, the potential for a favorable benefit/cost ratio (relative to no inspection or PMVI) is considered to exist for the following four areas:

- Brake performance
- Tire tread depth
- Brake lights
- Brake friction materials

TABLE 3-2. REVISED ACCIDENT BENEFIT OF SENSORS

Assumptions:	
No sensor impact on persons who ignore known defects	
100% sensor/display reliability	
Immediate corrective response	Lifetime Benefit (\$)
Brake performance	79.75
Tire pressure	39.11
Tire tread	22.78
Brake light intensity	4.84
Brake light electrical	4.84
Brake pad and lining wear	25.28
Steering play	8.70
Brake fluid leaks	22.40
Shock absorber	9.27
Front end alignment	2.02
Tire integrity	4.03

/

TABLE 3-3. POTENTIAL ECONOMIC IMPACTS OF ON-BOARD SENSORS

	Avg. cost/ veh. lifetime (\$)	Est. recoverable (max.) (%)	Max. benefit (\$)
Tires			
Tread wear (inflation)	14.40	100	14.40
Fuel consumption (inflation)	8.00	100	8.00
Tire failure (all causes)	10.40	50	5.20
		(inflation)	
Brakes			
Disc/drum refinishing	29.00	50	14.50
Disc/drum replacement	30.00	70	21.00

TABLE 3-4. RESULTS OF EVALUATION – CANDIDATES FOR ON-BOARD READOUT

	MAX PAYOFF			BREAKEVEN % EFFECTIVENESS	COMMENTS	POTENTIAL FOR FAVORABLE BENEFIT/COST
	SAFETY	ECONOMIC	SENSOR COST			
BRAKE PERFORMANCE	\$129	11	\$36-53	30-38%	CONCEPT DEVELOPMENT RECOMMENDED	YES
TIRE PRESSURE	39	28	185	100+	SIGNIFICANT COST BREAKTHROUGH REQUIRED	NO
BRAKE LIGHT	5	—		100+	MAJOR UNCERTAINTY IN PAYOFF	YES
PAD/LINING WEAR	46	35	\$ 2-15	3-18%	DATA BASE PRINCIPALLY ON DRUM BRAKES	YES
BRAKE FLUID LEAK	49	—	N/A	N/A	NO WORKABLE CONCEPT, VEHICLE RE- DESIGN POSSIBLE, DATA BASE UNCERTAIN	N/A

TABLE 3-5. RESULTS OF EVALUATION - CANDIDATES FOR OFF-BOARD READOUT

	SAFETY	MAX PAYOFF		BREAKEVEN % EFFECTIVENESS	COMMENTS	POTENTIAL FOR FAVORABLE BENEFIT/COST
		ECONOMIC	SENSOR COST			
BRAKE PERFORMANCE	\$129	21	\$30	31-55%	MAY MAKE SENSE FOR APPOINTED GARAGES COSTS HIGH WITH RESPECT TO DYNAMIC TEST MACHINES	YES
TIRE TREAD	46	-	?	?	IMPROVED INDICATOR - ADDITIONAL RESEARCH RECOMMENDED	NO
STEERING WHEEL	10	-	\$18	100+	IMPROVED PMVI PREFERRED CONCEPT	NO
PAD/LINING WEAR	46	35	2-15	3-21%	ON-BOARD READOUT PREFERRED	YES
BRAKE FLUID LEAK	41	-	N/A	N/A	IMPROVED INDICATOR/VEHICLE REDESIGN	N/A
SHOCK ABSORBERS	9	-	30	100+	SAFETY JUSTIFICATION QUESTIONABLE	NO
TIRE INTEGRITY	4	-	N/A -	N/A	NO WORKABLE CONCEPTS DATA BASE UNCERTAIN	NO
ALIGNMENT	2	5	\$15+	100+	CONCEPTS IDENTIFIED MARGINAL IN PERFORMANCE	NO

3.2 EVALUATION OF POTENTIALLY COST-BENEFICIAL SENSORS

For each of the four sensor areas judged to have a potentially favorable benefit-cost relationship, a synopsis of the sensor evaluations is provided.

The accident benefit limits defined by Table 3-2 for the 11 sensors listed have been compared with estimated sensor costs, other economic impacts, and the costs associated with alternative countermeasures such as periodic inspection. Complete results are discussed in Volume II of this report.

3.2.1 Brake Performance

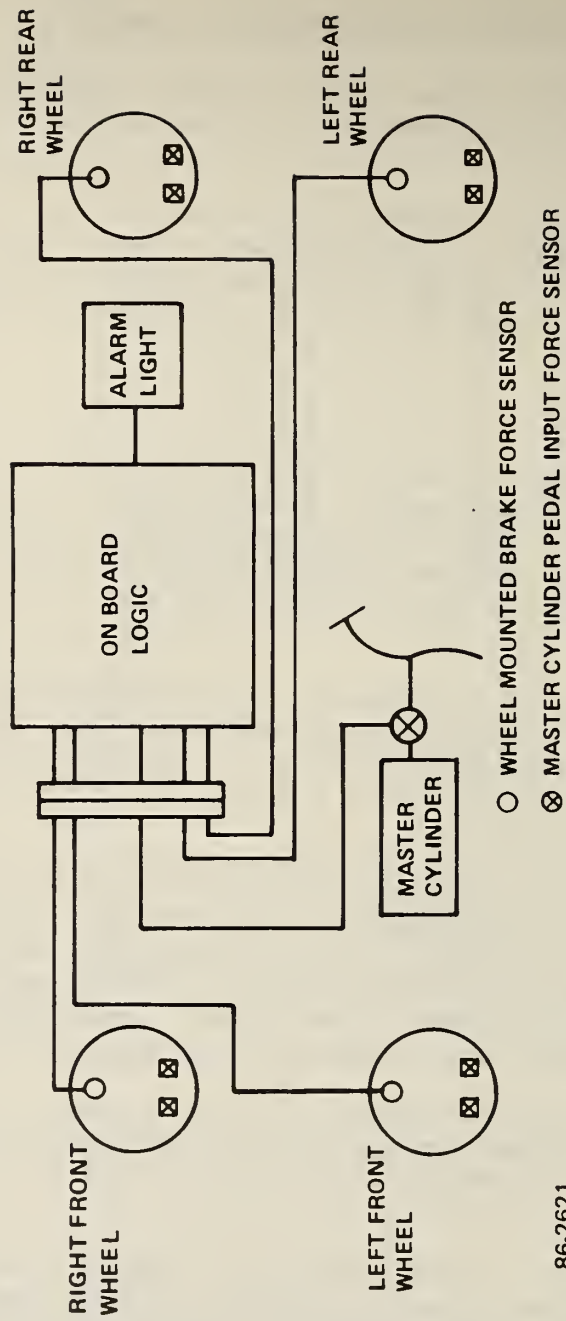
Undetected brake performance faults were the most frequently indicted vehicle factor in the Indiana study. A sensor with the capability to detect these faults by detecting an improper braking effort at one or more wheels would have a maximum (estimated) safety benefit of \$129 over the vehicle lifetime. The life cycle cost of such a sensor is estimated at \$67.

However, this sensor would also replace the existing differential pressure switch, yielding a cost savings estimated at \$14. The net cost of the sensor is therefore estimated at \$53. In addition, the sensor might provide economic benefits of reduced drum and rotor replacement whose value might be as high as \$11.

A fully implemented brake performance sensor (Figure 3-1) would consist of five semi-conductor strain gage force transducers -- one at each wheel and one on the brake pedal. The outputs of the sensors would be connected to a digital logic module capable of making comparisons between pedal load and total brake effort (gain), brake forces side-to-side (balance) and brake forces front to rear (proportioning).

Alternative brake performance sensors can also be conceived that utilize fewer transducers -- thereby providing less capability for less cost. The available data are inadequate to determine which is the preferred configuration.

Clearly, the estimated costs and benefits of a brake performance sensor are comparable. Moreover, a brake performance sensor appears to be competitive with PMVI as a countermeasure against brake defects. Perhaps the most important unanswered question is: "Will the device work as intended?" This question can only be answered by conducting a development test program. In addition, there are a large number of uncertainties as to the functional requirements for an imbalance sensor -- what conditions should be detected and at what threshold? Therefore, in



86-2621

Figure 3-1 BRAKE PERFORMANCE SENSOR (FIVE TRANSDUCER VERSION)

addition to recommending that development/feasibility work be undertaken for a brake performance sensor, it is also recommended that additional work be performed to define better the performance requirements for the sensor.

3.2.2 Tire Tread Wear

Tire tread wear was identified as the single most important specific cause of defect related accidents in the Indiana study. It occurred more often than any specific defect in the brake system. Collectively, however, brake performance faults occurred more often. As an area for sensor application, however, it was downgraded to third place because about half the drivers indicated an awareness of their tire condition prior to the accident. That is, they were trying to stretch the life of their tire. The accident cost of excessive tread wear has been estimated at \$22.78 per vehicle lifetime for the unaware drivers only and at \$45.56 for all drivers.

All passenger car tires intended for highway use are provided with "wear bars" molded into the tread which indicate the minimum safe tread depth. Although these indicators have negligible cost, the large percentage of unaware drivers in the Indiana cases suggests a need for an improved indicator.

A further confounding factor is the impact of the Indiana PMVI program. Although tread wear is a gradual process, accidents involving insufficient tread depth are as likely to involve recently inspected cars as cars nearly due for inspection. This is an indication that the Indiana PMVI system is ineffective. It is difficult to say whether this is because the inspections are improperly performed or because the rejection standard for tread depth is too low.

Because a real-time, in cockpit readout is not required, and annual periodic inspection may not be sufficiently often, the recommended approach to the problem of tread depth is an improved visual indicator. A colored indicator, visible at a distance to either the motorist or to law enforcement personnel, would be very desirable.

Based on a lifetime consumption of 12 tires for the average automobile, the break-even cost* for such an indicator would be between \$1.87 and \$3.75 per tire, depending on whether the indicator would be effective on drivers who currently try to over-extend their tire life. This analysis neglects the adverse economic impact of forcing tire replacement at an accelerated rate.

*Cost at which the benefit-cost ratio equals unity.

It may be difficult to incorporate an improved wear indicator without major impact on current tire manufacturing procedures. Additional research into this area is recommended.

3.2.3 Brake Light

The role of defective brake lights in accident causation is difficult to establish definitively. A review of the Indiana Level C investigations has placed the safety criticality of brake lights at 0.84 percent. The Level B investigations are more than an order of magnitude lower, at 0.06%. A preliminary subjective assessment by expert consultants has placed the number at an intermediate value of 0.12%. Based on the latter, the lifetime accident cost of defective brake lights is \$4.84.

There are two approaches to providing a sensor for brake lights. The optical approach involves the use of fiber optics or prisms to provide a display of brake light operation in view of the driver. The electrical approach involves the sensing of current flow in the brake light filaments in conjunction with the electronic logic to provide a warning indication. The former approach is more reliable, inasmuch as any failure of the brake light switch will be detected. The latter approach offers a superior display, since the warning indication can be latched (displayed when the defective element is not driven), and appears to be lower in cost.

An advanced electrical sensor, which incorporates a parallel switch to operate the sensor circuitry, has been costed at \$15. This sensor appears to provide all the capabilities of a fiber optic system, plus a superior display, at a lower cost. (Fiber optics cost estimate = \$17.) The large uncertainty in the potential accident benefit must be resolved before it can be determined whether sensors for brake lights are cost beneficial.

3.2.4 Brake Pad/Lining Wear

This area for sensor application is extremely controversial. There is general agreement that worn pads and linings have negligible effect on stopping capability, providing there is no exposed metal on the pad/shoe. The effect of metal-to-metal contact, however, is another subject. Limited laboratory and track testing have suggested that these conditions are both difficult to measure on dynamic test equipment and have negligible impact on vehicle performance. Analytical studies of drum brakes, however, indicate a marked sensitivity to the coefficient of friction between lining and drum, which has been corroborated experimentally. It is also recognized that metal-to-metal interfaces have different friction coefficients than lining-to-metal interfaces, particularly at high temperatures. Based on these considerations, the Indiana investigators have not hesitated to cite lining wear as a causal factor,

whenever metal-to-metal contact has been found in conjunction with physical evidence of brake malperformance.

Based on these two schools of thought, the accident cost of worn linings can be placed between zero and \$46, the latter figure based on the Indiana Level C data. However, the conversion to front disc brakes on American-made automobiles can be expected to reduce the upper limit, since disc brakes are less subject to the coefficient of friction in their performance.

The impact of wear sensors on brake repair costs is also difficult to estimate. It is known that substantial portion of brake service as currently performed involves disc and drum refinishing. It is not known, however, how this figure might be affected by sensors. Refinishing is often performed as a routine practice to ensure that the new pads/linings will conform immediately to the disc/drum without a prolonged break-in. If a 50% reduction in refinishing and a 70% reduction in disc/drum replacement are taken as upper limits on the service benefit, the lifetime savings of wear sensors is bounded by \$35.

There are many approaches to the problem of providing a wear indication. Numerous systems are currently available for disc brakes, and the technology for providing similar capability on drum brakes is also well understood. The tradeoff lies between electrical methods, which can provide a superior (in cockpit, latching) display and audible/tactile methods which are lower in cost. Our analysis estimates that the G.M. Squealer (currently provided on many G.M. cars) has a lifetime cost of \$1.80, and that electrical sensors can be provided for between \$10 and \$15. However, it should be noted that retail parts prices for some currently available electrical sensors are significantly higher than these estimates.

Another contender for brake friction material warning sensor would be an audible sensor that would produce a continuous warning sound when the automobile is moving. This concept overcomes the driver recognition problem of an audible alarm which makes a noise only when the brakes are applied. The estimated lifetime cost of this type sensor is \$7.20.

The benefit-cost ratio for brake wear indicators, and the preferred choice among the candidates currently available depends heavily on which of the conflicting estimates are adopted. However, the potential for a favorable result is clearly evident.

4.0 CONCLUSIONS

The conclusions of this study are of two basic types. Those of the first type relate to the requirements of the SOW and to specific on-board vehicle sensors -- whether they are cost-beneficial, what development work is required, and whether other regulatory action is indicated. For purposes of discussion, these conclusions are labeled "Technical". Conclusions of the second type, although not required by the SOW, are potentially more important, inasmuch as they impact the validity of the former. These conclusions are the outgrowth of a self-critical review of this study including both its methods and results. Although they are also technical in nature, these conclusions are labeled "critical".

4.1 TECHNICAL CONCLUSIONS

Utilizing a criterion of applicability in 1/2 of one percent of cases in the Indiana Tri-Level Studies in Accident Causation, (Level C investigations, Phases II-V) on-board vehicle sensors are indicated in the following areas:

- Brake performance.
- Tire (under) inflation.
- Tire tread depth.
- Brake light (electrical or optical).
- Steering wheel play.
- Brake pad and lining wear.
- Brake fluid contamination of friction material.

Based on limit performance studies, sensors for shock absorbers are also indicated.

Based on criticality of failure mode and data on failure frequency a sensor for tire integrity is indicated.

Based on the possibility of consumer economic benefits, an on-board vehicle sensor for front end alignment qualified for further consideration.

The scope of areas considered for sensor application has been restricted to the brake, tire, steering, suspension, lighting and signaling systems. Other sensors may be indicated in other areas.

In the eleven candidate areas considered, sensors have been found on currently available production automobiles in the following areas:

- Brake light intensity (Cadillac).
- Brake light function (Toyota, Honda).
- Brake pad wear (G.M., Volkswagen, Audi, Peugeot, others).

For all of the remaining areas, except tire integrity, it has been possible to postulate a sensing technique that would perform the function required. In some cases, however, the techniques identified are conceptual in nature, and would require additional study to determine their feasibility.

A preliminary cost benefit analysis has indicated that a favorable benefit-cost ratio may exist for the following sensor concepts:

- Brake performance.
- Brake lights.
- Brake pad and lining wear.
- Tire tread depth.

4.2 CRITICAL CONCLUSIONS

In addition to fulfilling the requirements of the statement of work, the work performed under this contract has led to some general conclusions about the strengths and weaknesses of the data bases that have supported it. These conclusions are believed to be of fundamental importance, since all conclusions drawn relative to specific sensor concepts can be no stronger (and no more valid) than the foundations upon which they rest.

It was recognized at the outset of this program that the data base was imperfect. The multi-stage algorithm used in determining the candidate areas represents an attempt to compensate for these deficiencies. The preferred method of analysis would have been to consult a definitive source on the role of defects in accidents (one based on a number of actual accident investigations) and to answer directly the question: "Is this specific vehicle condition a significant contributor to accidents?" However, at the outset of this program, it was believed that certain types of defects would not be detectable through direct accident investigation, and it was deemed necessary to employ other considerations.

Experience, however, has indicated that the combination of accident data sources with laboratory and analytical sources has been somewhat impractical, insofar as the development of quantitative information is concerned. Moreover, a data source on accident causation (Indiana) has been located which is of generally high quality in the scope of defects identified. As a result, this program has relied heavily on the Indiana Study as a source of data on sensor applicability. However, as a data source for any broadly based judgments in the VIU area, the Indiana investigations have six major limitations:

1. Small sample size (only 420 Level C cases).
2. Limited currency. (Present and future automobiles differ in important respects from those studied. Examples: disc brakes, radial tires, front wheel drive.)
3. Limited generality. (Although Monroe County, Indiana is average in many respects, it does not offer a sufficiently wide range of driving environments to be representative of the entire nation.)
4. Interactive effects are present. (The Indiana PMVI program may be affecting vehicle condition in ways that make extrapolation difficult to a non-PMVI environment or to a different inspection system.)
5. Apparent technical inconsistencies exist between the investigative data and laboratory experience. (See the discussion on metal-to-metal braking in Volume II.)
6. Data quality is not perfect. (A minor, rather than major limitation is the questionable judgment in a few specific cases. This may relate more to the documentation than the actual judgments themselves.)

Note that most of these limitations have been caused by conditions beyond the control of NHTSA and the Indiana personnel, and should not be construed as a criticism of either organization. It is believed, however, that this data base lacks the strength required to support rulemaking.

Accident data is not the only weak link in the chain of evidence supporting VIU activities. Indeed, these investigations have indicated that all critical areas are weak. Some of these weak areas, notably cost of periodic inspection and its effectiveness, are currently being strengthened. In other areas, however, there appears to be little activity. Specifically, the state of knowledge in the following areas is judged to be weak:

- Accident causation.
- Limit performance.

- PMVI effectiveness.
- Vehicle component degradation rates.
- Motorist/driver interface with the repair industry.
- Response of drivers to on-board sensors.

In summary, the authors have been constrained to soften their conclusions. Suggestions as to how the necessary facts (which would support stronger conclusions) might be obtained are included in Section 5.0

5.0 RECOMMENDATIONS

Consistent with the division of conclusions between sensor-specific technical judgments and critical conclusions regarding the data bases utilized in this study, these recommendations are of two basic types -- those which advance the technology of on-board vehicle sensors and those which address the data base needs described in Section 4.2.

5.1 RECOMMENDATIONS FOR ADVANCEMENT OF SENSOR TECHNOLOGY

- Development and test of a brake performance sensor. This development program should utilize the results of this study and ongoing NHTSA program such as the Optimized Brake Inspection, Manual Brake and Static Brake programs to refine the performance requirements for a brake performance sensor and then proceed to preliminary development and test of a brake performance sensor capable of meeting these performance requirements.
- Although current concepts of tire underinflation warning systems do not show a favorable cost benefit ratio due largely to estimated maintenance and replacement costs, the potential for low cost systems exists. The development of lower cost systems should be encouraged, so that their effectiveness can be evaluated.

Because reliability of current concepts is so questionable, it is further recommended that studies be made of the effectiveness of tire inflation sensors through field tests using existing sensing systems. The in-use capabilities of tire inflation sensors should be determined by installation of sensors on several hundred vehicles of various types. These could be government-owned vehicles, or privately owned cars. The sensors should be subjected to a full range of in-use environmental conditions, combined with the taking of data on how often sensor warnings were given and corrected by the vehicle operators. A program to conduct these tests might also be profitably combined with research into the existing tire inflation practices of the American motorist. The objective would be to answer questions relating to how and why surveys of tire inflation have shown a high incidence of underinflation.

- Conduct research into the feasibility of improved tread wear indicators. At issue here is whether improvements are possible without major changes in the manufacturing processes currently employed.
- It is recommended that the use of brake lining wear indications be encouraged.

5.2 RECOMMENDATIONS FOR DATA BASE IMPROVEMENTS

As discussed in the section on conclusions, many of the data base deficiencies relate to all vehicle-in-use programs, rather than simply on-board sensors. In this context, there is a need both for systems level analysis and specific, in-depth activities directed at specific research questions.

There has been a tendency toward specialization in VIU programs. For example, where once the entire topic of PMVI was subjected to analysis, we now find separate programs directed at brake system visual inspection and brake test equipment. This is generally a healthy trend, reflecting an increasing depth of knowledge in these areas. However, the "big picture" associated with motor vehicle programs is also changing. The automobiles of today differ in significant ways from those of the late 1960's when some of the pioneering work in systems analysis of automotive safety problems were performed. Among the most important changes are the introduction of front disc brakes, and the general trend toward radial tires. In addition, the economics of inspection, accidents, and automobile maintenance have been continually changing.

To keep the big picture in focus, it is necessary to update these studies, taking as the subject not one of the possible VIU countermeasures (PMVI, on-board sensors, vehicle design) but all of them at once.

A key area is the determination of consistent and reliable safety criticalities for all of the important subsystems of the automobile. The long-term solution to this problem is more accident investigation. It is believed that about 10,000 new accidents should be investigated to a level equivalent to that employed in Level C of the Indiana study, incorporating methodological improvements derived from the use of the existing data. Specifically, the accident sampling procedures should be refined to incorporate a representative national sample, and stratified to strengthen the data base in fatal and injury producing accidents. The analysis of each case should more carefully quantify the indictments made, rather than simply use the labels "certain", "probable", and "possible." The interface between field and laboratory studies should at all times be closely studied.

The development of the needed safety criticality data using accident investigation will require many years -- 10,000 cases might be accumulated at 2,000 per year for 5 years. Before this is completed, attempts should be made to improve on the estimates and sources used in this report. One possible improvement is the use of analytical techniques to develop interim estimates. Except for the activities reported under this program, this was last done in 1970 by Booz-Allen Applied Research, using techniques and sources of information markedly inferior to those available today. It is recommended that a new, broadly based analytical effort be undertaken to generate interim estimates.

In addition to the basic needs for safety criticality information, other unknowns in the behavioral area require resolution. The data base on owner knowledge of (and response to) simple sensors such as the brake failure indicator, high-beam indicator, alternator/generator light, and oil pressure warning light is presently very sketchy. This data could profitably be collected in conjunction with future vehicle condition surveys similar to those conducted under the NHTSA sponsored Motor Vehicle Inspection Evaluation Program (MVIEP).

Information on the motorists' awareness of vehicle condition is also essential. This data should continue to be collected in accident investigations and should also be incorporated in vehicle surveys.

Parts return programs and other repair industry programs should be exploited to characterize more fully the current repair practices of the American motorists.

If NHTSA must justify its programs against increasingly anti-regulatory attitudes in Congress and elsewhere, the collection of stronger data is a necessity.

TL 242 .H36
HELDT, R.
ON-BOARD VE
TECHNOLOGY

Form DOT F 1720
FORMERLY FORM DO

DOT LIBRARY



00092264